U.S. Application No. 10/601,321
Filed June 20, 2003
Docket No. IMEC278.001AUS

CERTIFICATE OF ACCURATE TRANSLATION

I, Andre Clerix, of Interuniversitair Microelektronica Centrum (IMEC), located at Kapeldreef 75, 3001 Leuven, Belgium, do hereby certify that I am conversant with the English and Dutch languages and am a competent translator thereof, and I further certify that to the best of my knowledge and belief the attached English translation is a true and correct translation made by me of selected portions of the document entitled "Samenvatting", which was filed in U.S. Provisional Application No. 60/390,883, filed on June 21, 2002, from which U.S. Application No. 10/601,321, filed on June 20, 2003, claims priority.

Dated: 16th November 2003 By: _____
Andre Clerix

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PATENT

Case Docket No. IMEC278.001AUS
Date: December 3, 2003

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s)	:	Magnus, et al.
Appl. No.	:	10/601,321
Filed	:	June 20, 2003
For	:	METHOD OF FORMING QUANTUM-MECHANICAL MEMORY AND COMPUTATIONAL DEVICES AND DEVICES OBTAINED THEREOF
Examiner	:	Unassigned
Group Art Unit	:	2819

I hereby certify that this correspondence and all marked attachments are being deposited with the United States Postal Service as first class mail in an envelope addressed to: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450, on

December 3, 2003
(Date)

Mark M. Abumeri, Reg. No. 43,458

TRANSMITTAL LETTER

Commissioner for Patents
P.O. Box 1450, Alexandria, VA 22313-1450

Dear Sir:

Pursuant to **37 C.F.R. § 1.78(a)(5)(iv)**, as revised on July 1, 2002 the Applicant submits the following in the above-identified application:

(X) A Certificate of Accurate Translation in one (1) page.

(X) English-language translation in fifteen (15) pages of selected portions of a Dutch document entitled "Samenvatting", the entirety of which was originally filed in the Dutch language in a prior-filed Provisional Application No. 60/390,883 on June 21, 2002, from which the above-identified application claims priority; Applicant notes that it has not been notified or given a period of time within which to file the English-language translation of the Dutch document; Applicant thus submits the enclosed English-language translation *sua sponte*.

(X) The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment, to Account No. 11-1410.

(X) Return prepaid postcard.

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TRANSLATION OF SELECTED PARTS FROM THE MASTER THESIS

Implementation Of A Q-Bit On Silicon

Master thesis

Chapter 1 The quantum computer

This chapter only contains prior art information that can be found in other public available documents.

Chapter 2 The quantum ring as q-bit

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In this chapter a novel concept for building a quantum computer is taken up: quantum rings. This is a project of the TCAD group (division STDI).

A freestanding, closed, superconducting aluminum ring forms a *quantum ring* (figure 2.1). To realize such structures, the accuracy and purity of semiconductor technology will be employed.

This chapter starts which a general exposition of the concept of superconductivity. In a next paragraph it will be extensively shown how superconductivity will result in a quantization of the flux through a closed ring. Of importance is how such superconducting ring can be used as quantum bit. Next the problem of communication with the outside world will be dealt, and the communication between the individual bits, necessary to obtain the final quantum computer. The change in eigenstate, and the equipment necessary to measure this change (M.F.M), is briefly discussed. Finally an overview is given of the requirements the structure to be formed such meet. All relevant conclusions and numerical data from this chapter will be summarized as basis for the next chapters. The role of this chapter in all this shall also be detailed.

Figure 2.1. a quantum ring

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2.1 Super conductivity

If one would ask a person having average scientific skills what superconductivity means, he would probably answer that it concerns materials that, when be cooled below a critical temperature, will conduct electrical currents which will not experience resistance. He will describe an ideal conductor, namely a material having an electrical resistance equal to zero. In an aspect he is correct: a current in a superconductor will not see any resistance. But stating that a superconductor equals a perfect conductor is not correct, something more is going on.

From experiments it is shown that in the interior of a superconducting structure no magnetic field exists. If an external applied magnetic field would be present in this material, then at the transition to a superconducting state, this field will be expelled to the outside. This perfect diamagnetism is inherent to superconductivity, and is called the Meissner-effect.

The compensation of external applied magnetic fields can be described by magnetic vectors M in the material, which will position them in a direction as to oppose the applied field. In this configuration the internal energy will increase with increased field force according to $dW = - M\, dH$, with M being the external work done on the system. Thermodynamics predicts that a state can only be stable if its free energy is lower than the free energy of all other possible states. It is not surprising that, for a given critical field the superconducting state will be lost and the electrons will return to the normal configuration. Not only is there a critical temperature Tc, but also a critical magnetic field will determine whether or not a material will be superconducting. Both are linked: at lower temperatures the maximum allowable magnetic field Hc will be higher. At $T = Tc$, is $Hc = 0$.

There exist also a difference between type I and type II superconductors. A type I superconductor only has one critical Hc, a type II superconductor has two critical transition values Hc, in between which this superconductor is in a so-called *vortex state*, being a kind of transition region. Aluminum is a type I superconductor, and has a critical transition temperature of about 1.23K and below this temperature, a critical magnetic induction $Bc = uc\ Hc$ of about 10 mT.

Taking all this into consideration one would in first instance say that the phenomenon of superconductivity can be describe by making the resistivity ρ equal to zero in Ohm's law $E = \rho J$ and in the equation $M = \chi H$, the susceptibility χ equal to -1. However some fundamental objections can be raised. **(p17).** Ohms law for example is only applicable for steady state situations, and doesn't say anything about the effect a temporary electrical field might have on current density. Also the proposition that the B-field would be zero everywhere is not quite right: during experiments with superconducting thin films (10nm) a penetration of the field has been observed. Also for bulk superconductors there exists directly underneath the surface a transition region from the external field to a zero-field inside. Furthermore from the assumption that $\chi = -1$ doesn't provide any physics insight why this would be.

2.1.2 London equation

All these arguments bring us to a different approach. We drop Ohm's law, and the description of diamagnetism by using magnetic vectors M. Instead we propose the following alternative mathematical description:

Formula 2.1

This is the London equation [3]. We will now show how this will bring us to the Meissner-effect and the concept "penetration depth". This equation will allow us to gain more insight in what really happens in a superconductor. Maxwell's laws remain unchanged. In a magnetostatic situation therefore the following is valid:

Formula 2.2

If we take the rotor of both sections and taking $\nabla B = 0$ into account, then:

Formula 2.3

Combining this with (2.1) we obtain:

Formula 2.4.

If we have a closer look at this equation, we see that a uniform (constant over the whole space) B-filed is no solution of this equation, unless this field equals zero. The only possible field distribution allowed by this equation will be exponentially damped when entering the superconductor. An example will better illustrate this: consider the halfspace $x < 0$ as the environment and the halfspace $x > 0$ as the superconductor. Along the z-axis a uniform external field Bo is applied for $x < 0$. Solving equation (2.4)

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figure 2.2: The Meissner-effect in a superconducting material

in case $x > 0$. The equation will be reduced to a single equation for the z-component of the magnetic field:

Formula 2.5

with boundary condition:

$Bz = Bo$ for $x = 0$

This has as solution (figure 2.2):

Formula 2.6

This result is nothing less than the action of the Meissner-effect. This is what happens in more realistic situations: the magnetic field will decay in an exponential way inside the superconductor. The perfect diamagnetism inside a superconductor is a result of a very special current distribution, described by the London equation. It doesn't involve magnetic dipoles, which are responsible for more classic magnetic phenomena.

Furthermore we notice that if the magnetic field is zero inside the conductor, also the current density will be zero (according to the Maxwell equation (2.2)). This means that the superconducting currents will always flow near the surface and never inside the material. They will flow such that deeper into the material they will extinct the magnetic field in an exponential way, until it becomes negligible.

We also see that the λL, *the London-penetration depth*, is a measure for the penetration of the magnetic field. In case of aluminum it is about 16nm at 0K.

2.1.2 BCS theory

The basis for a quantum-theoretical study of superconductivity was formed by Bardeen, Cooper and Schrieffer in 1957. They proved that, below a critical transition temperature, electrons are grouped in pairs in the reciprocal space. If the state having a wave vector k and spin up is occupied,

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than also the state having wave vector –k and spin down is occupied. These are the so-called Cooper pairs. Because these pairs have an integer spin 0, they can be considered as boson-particles. This implies inter alia that electron pairs can condensate in the same state.

The grouping in pairs gives rise to a lowering of the internal energy. The difference in energy between the normal state of an electron and the paired state can be superimposed on the band diagram of the lattice . This difference in energy is a kind of "energy gap" over which electrons can be excited. At 0K all electrons in the conduction band will be grouped in pairs, and be below the gap. At temperatures above 0K the pairs will be split apart, and hence also states above the gap will be occupied.

Only the electrons pairs will contribute to the superconducting current. At temperatures above 0K the normal "rest electrons" will form a classical current and dissipate heat. Normally the contribution of these electrons to the current density is negligible, because due to their higher electrical resistance, they are being short-circuited by the Cooper-pairs.

The London-equation (2.1) can be conducted from the BCS theory. This can be demonstrated as follows, for a simplified case. One can consider a boson-gas (our electron pairs) having a large number of bosons within the some orbital (a situation comparable with a beam of photons all having the same wavelength). The probability amplitude for such gas can be derived in a classical way, because we're dealing with identical particles, which are equal in all aspects. This probability amplitude can be put to par with something we can observe macroscopically: the concentration of electron pairs. This reasoning no longer holds for a gas of unpaired electrons, because they constitute fermions, which must all be in a separate state because of the Pauli-principle. We assume the concentration of electron pairs $n = \psi\psi^*$ is constant over the space. At zero degrees Kelvin this n is equal to half the concentration of conduction band electrons. We can state that:

Formula (2.7)

From classical mechanics we known that the Hamiltonian of a particle having a charge –q and mass m in electromagnetic field, in the absence of a conservative electrical potential, equals:

Formula (2.8)

If we use the Hamiltonian

Formula (2.9)

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we can derive the velocity v:

Formula (2.10)

In this formula the impulse v is a "generalized impulse". In quantum mechanics this impulse will be replace by $\frac{\hbar}{i}\nabla$ if we are dealing with the r-space. The quantum mechanic expression for the speed is obtained when replacing the variables impulse and speed by their corresponding operators:

Formula (2.11)

From quantum mechanics we known that the current density is given by

Formula (2.12)

We can further rewrite this as

Formula (2.13)

If one would take the rotor from the above expression and, remembering that the rotor of a gradient is always zero, we finally obtain the London-equation

Formula (2.14)

In this equation q = 2e with –e being the electron charge, and m being the effective mass of a Cooper pair. When comparing this with (2.1) we can extract from this the penetration depth λL:

Formula (2.15)

This allows us to calculate λL. In case of Aluminum we will find 16nm.

2.1.3 Coherence length

Having dealt with the London penetration depth, we must also consider that other very important parameter characterizing a superconducting material.

The London equation links the local variables current density and magnetic vector potential. If, however, different phases are present within the same lattice, one phase being superconductive, the other one not, then the London equation fails. In such a situation the notice coherence length tell us something about the spatial variation of A

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and J in the transition region. A large coherence length is indicative of a considerably large transition region, while a small coherence length suggests a small transition region.

The coherence length was first used in the equations of Landau and Ginzburg. These equations allow us to calculate the wave function of the Cooper pairs in a given superconducting lattice, be it in a simplified quantum mechanical approach. In this context it indicates the distance at which the wave function will not change drastically. A large coherence length would mean a large spatial "connection" of the system's wave function. This has to do with the stability of the Cooper pairs. It doesn't mean that once a Cooper pair is formed that those electrons will be paired forever. Actually a dynamic equilibrium exists between the generation and annihilation of Cooper pairs. A large coherence length is caused by Cooper pairs having a long lifetime.

Conclusion: the coherence length is a measure for the spatial connection of the superconductive state. This connection will require a minimal distance between the two phases (one superconducting, the other not), if they have to co-exist. If this distance is not present, consequently only one of these two phases will remain. The coherence length ξ_0 of Aluminum is about 1.6um.

2.2. Flux quantization and eigenstates of the superconducting ring

Considering a closed, superconducting ring as shown in figure 2.1. The ring is thick enough, such that the magnetic field inside can decay to zero. Inside both B and J equals zero. In order to obtain a current density (2.13) of zero magnitude, the following must apply:

Formula (2.16)

We now take the line integral, along a closed contour line C within the ring:

Formula (2.17)

This is the phase change if we would circulate only once. Because the wave function ψ is an unequivocal variable, ψ can only have one value in each point, hence

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Formula (2.18)

with s being an integer. If we take the integral of the vector potential on the right in (2.16), and we use Stokes' theorem, than we obtain:

Formula (2.19)

with O being an arbitrary surface enclosed by C and Φ being the flux through the ring. If we now use (2.18) and (2.19) in (2.16) than

Formula (2.20)

The flux through the ring is thus quantized, and is an integer multiple of the flux quantum Φo. Experiments prove that q is twice the elementary charge e, so:

Formula (2.21)

The current flowing at the surface, will accommodate itself to the external applied field, such that condition (2.20) is met: the sum of the applied field and the field induced by the current, will always be an integer multiple of the elementary flux quantum.

This quantisation effect is the essence of the quantum computer project of the TCAD group. In case of our q-bit we can use the states |0> (no flux), |1> (one flux quantum up) and |-1> (one flux quantum down). This way we have three mesoscopic eigenstates for our ring having as corresponding eigenvalues different integer amounts of flux. Only these eigenvalues are the only values obtainable when measuring the state of the ring. The actual current distribution across the ring is unimportant, it is the flux identifying the state.

It is not clear yet, which possible states will be used, but in principle it could be more than two. This implies that algorithms making use of our system have to deal with an equal amount (for example three) possible values for each digit.

When applying an external magnetic field of sufficient magnitude the bit can switch from one state to another. This external magnetic field can originate from input rings or other quantum rings.

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Figure 2.3: simulation of a quantum ring in state |1>

A more detailed explanation of the quantum mechanical behavior of the quantum ring can be found in the master thesis of Geert Enneman. In this thesis he examines the actual current distribution across the ring taking into account the specific geometrical shape of the ring. Figure 2.3. is one example of these calculations. We can see how one quantum ring sustains one flux quantum in the absence of an external magnetic field. The figure shows the vector potential and the magnetic induction and current density derived from it.

2.3. Flux conduction and communication with the external world

As outlined above we need an external magnetic flux that can be guided through our rings. If we can supply a given current to an input ring, and guided the flux, induced by this current, through our quantum ring, we're fine. The concept of the classical transformator appears: a closed iron core guiding the flux as desired (figure 2.4). In this figure only the parameters are indicated that affect the input- and output signal.

Our input signal is always a current, resulting in a magnetic flux. Between these two parameters a linear relationship exist (not taking into account the hysteresis curve of the ferromagnetic material). This magnetic flux will be guided through our superconducting ring. The ring will conduct the current necessary to maintain the flux quantum. The exact conditions to switch from one quantum state to another will be discussed in the next paragraph.

Figure 2.4: a quantum ring with input and output ring

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Our output signal is an electrical field in the output ring, induced by a time-dependent magnetic flux. This flux originates from our quantum ring and is induced by the superconducting current in the quantum ring. Between the superconducting current and the output flux the same linear relationship exist as between the input current and the input flux because we're dealing with the same ferromagnetic core. The output signal provides us with information about the change in time of the current through the quantum ring. To derive relevant conclusions from this output signal it will be necessary to know the behavior of the superconducting current when changing from quantum state.

Simulation programs are an indispensable to study such behavior: the relationship between input signal, output signal and the state of the superconducting quantum ring.

The following important remark can be given: despite they are cooled down below Tc, the input- and output ring will not become superconducting as they are in galvanic contact with the external world. We have to keep in mind that the Cooper pairs are coupled in the reciprocal space but not in the real world. This means that one electron of such pair can be at large distance from the other electron (in real distance). To obtain the superconducting state, it is necessary that both electrons of the pair are located in a lattice below Tc. Because the "environment lattice" is much larger than the cooled lattice, almost no Cooper pairs will be present within the volume of the input- and output ring.

2.4. Changing the eigenstate

If the superconducting current will accommodate itself such that the flux quantum through the ring is maintained, how will we ever be able to change this quantum? The answer to this question is given by the critical magnetic inductance B.

As discussed earlier, there exist for the magnetic field in a superconductor a critical value, above which the superconducting state will be lost. This magnetic field can be external, but it might as well originate from the superconducting current itself.

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If the current density exceeds a given critical value Jc, then the superconducting state will be lost at this point. The relationship between Jc and Bc is given by Maxwell's law (2.2).

We can increase the superconducting current through our ring by applying an external field by means of our input ring (figure 2.4). The quantum ring will counteract this increase by inducing a higher counter flux. This implies a larger current density at the inner side of the ring. This way the current density in the ring can be that high that it will reach its critical value.

When this happens, it will result in a normal state with a normal current at the inner side of the ring. The dimension of the region in which this normal current is present is of the order of magnitude of the coherence length. In this respect it is advantageous to have a coherence length, which is not order of magnitudes smaller than the dimensions of the ring. If this would be the case, the danger exist that small regions in the lattice would act on their own, as they can become independent from the other lattice regions.

If such a normal current is created, this current will transfer its kinetic energy to the lattice, causing the current density to decrease. The total flux through the ring can now increase in the direction of the applied flux. The ring, which is now in a normal non-superconducting state, can lower its energy to become superconducting again. This time the flux quantum will differ from its previous value. The surface currents needed to maintain this flux quantum can be conducted without exceeding the critical value.

Using simulation programs such as developed by Geert one could calculate which input flux is needed to change the given state of the ring with one flux quantum. This would be the input flux resulting in a (local) increase of Jc when maintaining that state (that multiple of the flux quantum).

2.5. Measuring by means of M.F.M.

Although it is the final aim to read out the state of the bit by means of the output ring, in a first stage of the project Magnetic Force Microscopy will be used to show the flux quantization and the change in eigenstate.

In case of M.F.M a (very sharp) needle scans the surface, as is the case with A.F.M. (Atomic Force Microscopy). The distinction between these two is that in case of M.F.M the needle comprises a layer of magnetized material. The magnetic field of the needle interacts with the field in the material under examination. The attractive force between needle and surface gives information about the magnetic state of the surface. M.F.M. is a very accurate measurement technique, and is often used to map magnetic domains.

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Figure 2.5.

By means of an M.F.M set-up (in a cryostat) we want to show that the flux through the ring is quantized. We can measure the field in the two cores and integrate over the complete width of the core. If we sum up these two fluxes, neglecting the stray flux (which could be estimated as well) the sum must remain the same, independent of the

input current. However, if it would change by increasing input current, this change would be a difference of one flux quantum compared to the previous state.

The equipment needed is available at the physics department, faculty applied sciences of the K.U.L.

2.6. Ring matrix

The final goal is to build a complete quantum computer, which would look as follows (figure 2.5): a matrix of freestanding rings, magnetically coupled to each other and to the input- and output rings. An important feature is that the quantum rings can change each other's flux quantum.

The ring matrix needs not to be a square, but will, in practice, comprises much more rings than suggested by the figure. One row from the matrix could represent one bitstring. The concept is that when applying appropriate input signals and interpreting the output signals in correct way calculations can be done. Which signals are needed is not clear yet and is a future challenge.

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2.7 Summary of the objectives.

In a first stage of the quantum-computing project of the TCAD group is to manufacture a single quantum ring with input- and output ring.

It is not needed to already obtain a useful signal out off the output ring. The measurement of the state will in the mean time be done using M.F.M. It must be possible to change the state of the ring with one flux quantum by means of a current through the input ring.

2.7.1. Aimed specifications

The first objectives can be summarized as follows: make the structure of figure 2.4 having the following specifications:

- the quantum ring must be made superconducting in a cryostat and this state may not be lost due to possible external H-fields > Hc during operation
- the Meissner-effect must be as complete as possible, such that equation (2.16) becomes applicable and flux quantisation takes place. This means that the penetration regions, being present at all sides of the surface, should (almost) not overlap
- the input- and output ring must always be in contact with the external world and conduct a current
- the ferromagnetic core must guide the magnetic flux needed to destroy the superconducting state of the quantum ring in order to add a flux quantum
- the input ring must be able to induce such a flux
- the magnetic coupling between the rings must be as strong as possible. This is important for the coherence between the bits in the final quantum computer

- the structure must be suitable for a (low temperature) M.F.M set-up
- the cryostat must be able to offer as low as possible temperature (T<<Tc) to minimize the concentration of normal unpaired electrons and to approach as much as possible the ideal situation (a conduction band consisting of only Cooper pairs). It is important that not too much heat is being dissipated. Heat dissipation will manifest itself in different ways: both in the input- and output structures as well in the quantum ring itself during the transition of a flux quantum, and also in the ferromagnetic cores for time-dependent magnetic fluxes (eddy currents)

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Table 2.1 Numerical data concerning superconductivity and flux quantisation

2.7.2 Important numerical data

The following numerical data (table 2.1) are of importance.

Aluminum is a well-known and successfully applied material within semiconductor technology. That is way it is our preferred choice as superconductor. However we don't want to exclude Niobium, because, from all elements, it has the highest Tc. The physics department of the K.U.L has experience with this metal as superconductor and even has the vaporization equipment to deposit thick niobium films.

We suggest that both metals can be cooled well below their critical transition temperature, such that the values in table 2.1 at 0K are close to their real values. In case of Aluminum things might be complicated while in case of Niobium this will be straightforward.

Chapter 3 Process features

3.2. Process options

The processes that are being discussed have most of the their steps in common. The major difference is the construction of the ferromagnetic core. The last two proposals use galvanic processes to create the core, the first one doesn't. Galvanic processing is the depositing of thick layers of metal using electrolyse. This is a relative easy process, but the III-V group of IMEC doesn't have such a set-up. That is way in this stage the first process is used by us.

The three processes presented will be illustrated in schematic drawings. The drawings are not to scale, especially in the vertical dimension. In reality the structure will be much flatter.

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figure 3.3. process 1 without galvanic processing
a) Si with thermally grown oxide b) sputtering of NiFe c) oxide deposition, evaporation of Aluminum structures, d) oxide deposition and etching of holes e) sputtering NiFe

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3.2.1 without galvanic processing

The process sequence is schematically illustrated in figure 3.3. It comprises the following steps:

- We start with a silicon wafer with an oxide, which might optionally be thermally grown (A)
- We create a pattern in a photoresist (mask 1). We sputter a thin layer (50nm) NiFe and perform a lift-off. The process result is shown in (B)
- Thereafter we deposit an insulating nitride or oxide layer. If we want to minimize the topographical effects, introduced by the previous layer, we can make this layer relatively thick (200nm). In this specific process it is important to make this layer as thin as possible (e.g. 50nm)
- Again a photoresist layer is deposited and exposed using mask 2. A thick layer of Aluminum is evaporated (200nm) and again lift-off is performed. Now the rings and the Aluminum connections with the outside world are made. The result is shown in (C).
- A nitride or oxide layer is deposited. This can be relatively thick (400nm) because of fencing of the Aluminum structures (see lift-off section), but it might as well be very small if we use negative resist to create the Aluminum structures. In this specific process it is of importance that this layer is as thin as possible.
- A photoresist pattern is formed to define the holes to be etched (mask 3). A dry etch step is performed. The result is shown in (D).
- The most difficult step is now to be done: sputtering the second NiFe layer. Again we use mask 1 and the lift-off method. Most critically is the complete coverage of the sidewalls of the holes. This is the reason why these holes should not be to deep. The result is shown in (E).
- What still has to be done is to release the bondingpads (large Aluminum pads to contact the input and output rings). These are covered with oxide or nitride. We use a fourth mask and a dry etch step.

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Figure 3.4. process 2 with a single galvanization step
a) Si with thermally grown oxide, b) evaporation of Au, sputtering of NiFe c) deposition of oxide , evaporation of Aluminum structures, d) deposition of oxide and etching of the holes, e) sputtering of NiFe and formation of the photoresist pattern, f) galvanic plating of NiFe, g)removing the photoresist, pattern the NiFe layer by etch

3.2.2. with a single galvanic step

The process sequence is schematically illustrated by figure 3.4. It comprises the following steps:

- We start with a silicon wafer with an oxide, which might optionally be thermally grown (A)
- We deposit a conductive layer (e.g. Au). This is needed for the galvanic process, as will be explained further on.
- We create a pattern in a photoresist (mask 1). We sputter a thin layer (50nm) NiFe and perform a lift-off. The process result is shown in (B)
- Thereafter we deposit an insulating nitride or oxide layer. If we want to minimize the topographical effects, introduced by the previous layer, we can make this layer relatively thick (200nm).
- Again a photoresist layer is deposited and exposed using mask 2. A thick layer of Aluminum is evaporated (200nm) and again lift-off is performed. Now the rings and the Aluminum connections with the outside world are made. The result is shown in (C).
- A nitride or oxide layer is deposited. This can be relatively thick (400nm) because of fencing of the Aluminum structures (see lift-off section), but it might as well be very small if we use negative resist to create the Aluminum structures. In this specific process it is of importance that this layer is as thin as possible.
- A photoresist pattern is formed to define the holes to be etched (mask 3). A dry etch step is performed. The result is shown in (D).
- Again we sputtering a NiFe layer. The sidewalls need not to be covered (E). This layer will also be used as conductive surface during the galvanic process. The pattern of mask 1 is again defined in a photoresist layer. The Au layer is connected to an external electrode. This way the cathode is formed. If the wafer is put into the electrolytic bath, the positive metal particles will be deposited on this electrode. With this method thick NiFe layers can be formed.

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- After executing the galvanic process the photoresist is removed. The parts of the NiFe that were not exposed need to be removed. We use a dry etch over the entire wafer, having as effect that also the electroplated part will be thinned slightly. The endresult is shown in (G)
- What still has to be done is to release the bondingpads (large Aluminum pads to contact the input and output rings). These are covered with oxide or nitride. We use a fourth mask and a dry etch step.

3.2.3. with two galvanic steps

This process is similar to the previous one, but it is a bit more complicated. The reason to use this process is to obtain a core having a larger cross-section. (see chapter 5). The following steps are different:

- In this process also the first NiFe layer is electroplated. This way we form cores without any small cross-sectional area.

- After depositing the first oxide, which will have the same topography as the core below, the surface has to be planarized in order to avoid unwanted deformation of the Aluminum rings. This can be done using mechanical polishing of the oxide or nitride.

The complete sequence is shown in figure 3.5.

3.3. Remarks

- the sputtering of the NiFe is critical regarding the sidewall coverage in the first process option. Sputtering at different angles seems to be a good idea to improve the sidewall coverage. Unfortunately this approach was not possible at IMEC.
- The first two process options etch the oxide or nitride down to the underlying NiFe. Because this NiFe is very thin, it might be that an etch-stop layer is needed (1 to 5 nm Chromium). This Chromium can be deposited uniformly over the wafer after the first NiFe layer. Chromium is a non-magnetic layer having the same permeability as air or vacuum. From magnetic point of view, this Chromium layer constitutes an airgap in our core. This has consequences on the core inductance, because 1nm of air corresponds to about 50 um NiFe.

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Figure 3.5. process 3 with two galvanic steps
a) Si with thermally grown oxide, b) evaporation of Au, sputtering of NiFe, form photoresist pattern, c) electroplating NiFe, d) remove photoresist, deposite oxide layer and polish, e) evaporation of Aluminum structures, f) deposition of oxide and etching of the holes, g) sputtering of NiFe and formation of the photoresist pattern, h) galvanic plating of NiFe, I) removing the photoresist, pattern the NiFe layer by etch

- If we want to avoid oxidation of the exposed NiFe we can passivate this layer covering it with Copper. Therefore we deposit Copper uniformly over the wafer. We can use the same sputter tool as used for NiFe.
- Depositing of thick NiFe layers in process 2 and 3 can be done using galvanic processing. Although not possible at IMEC but it might be possible to use the evaporation set-up also for NiFe. This way much thicker layers can be formed without the need for a galvanic process step.

Chapter 4 Designing the masks

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5.5. Conclusions from this chapter

The followings items are of concern when designing the rings and the core;

1. Make sure the cross-section of the core is uniform along the core and as large as possible. It is the smallest cross-section which determines the Bmax
2. Use as efficient as possible the available area within the ring to minimize the diameter of the ring and the stray inductance Lstray as much as possible. That is way the bottom and top part of the core must be as thick as possible (hich implies the use of process option 3). This is also important for the coupling of the bits (maximize the ratio core inductance Lcore/stray inductance Lstray)
3. An airgap might help the reduce the Bmax, but it will also reduce Lcore/Llek (worsen the coherence)
4. The input ring should be at least 9 um large (to not exceed the limit of 1mA/cm2)

Table 5.6 contains some suggestions (with reference to process option 3) taking into account the above rules. We clearly see that trade-off between the coherence (determined by the ratio Lcore/Lstray) with the reduction of (Bmax) when increasing the airgap. The Chromium longer not only is used as an etchstop layer, but also to lower the inductance of the core without changing the cross-sectional area.

For our preliminary application, i.e. a single quantumbit, coherence is of minor importance.

Table 5.6 characteristics of core and input signal for process 3

Chapter 6 The output signal

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6.3. suggestions to increase the signal amplitude

1. Make the inductance of the core as large as possible, hence the core should be as large as possible. This implies *djuk* to be as large as possible, which is also advantageous to reduce the Bmax in the air gap. It eliminates the opportunities offered by an airgap for reduction of the Bmax
2. The output ring should in the form of a planar coil and the output signal will be multiplied by N, the number of coils. The outer coils of the planar coil constitute a large impedance which indicates adding coils is not always an advantage the number of coils should . One could then use multileveled coils.
3. When possible for the given dimensions of the core, Niobium should be used instead of Aluminum. Niobium has a critical current level, which is 30 times higher than the Aluminum. Preferably the input and output ring are not made of Niobium because of its low electrical conductivity.